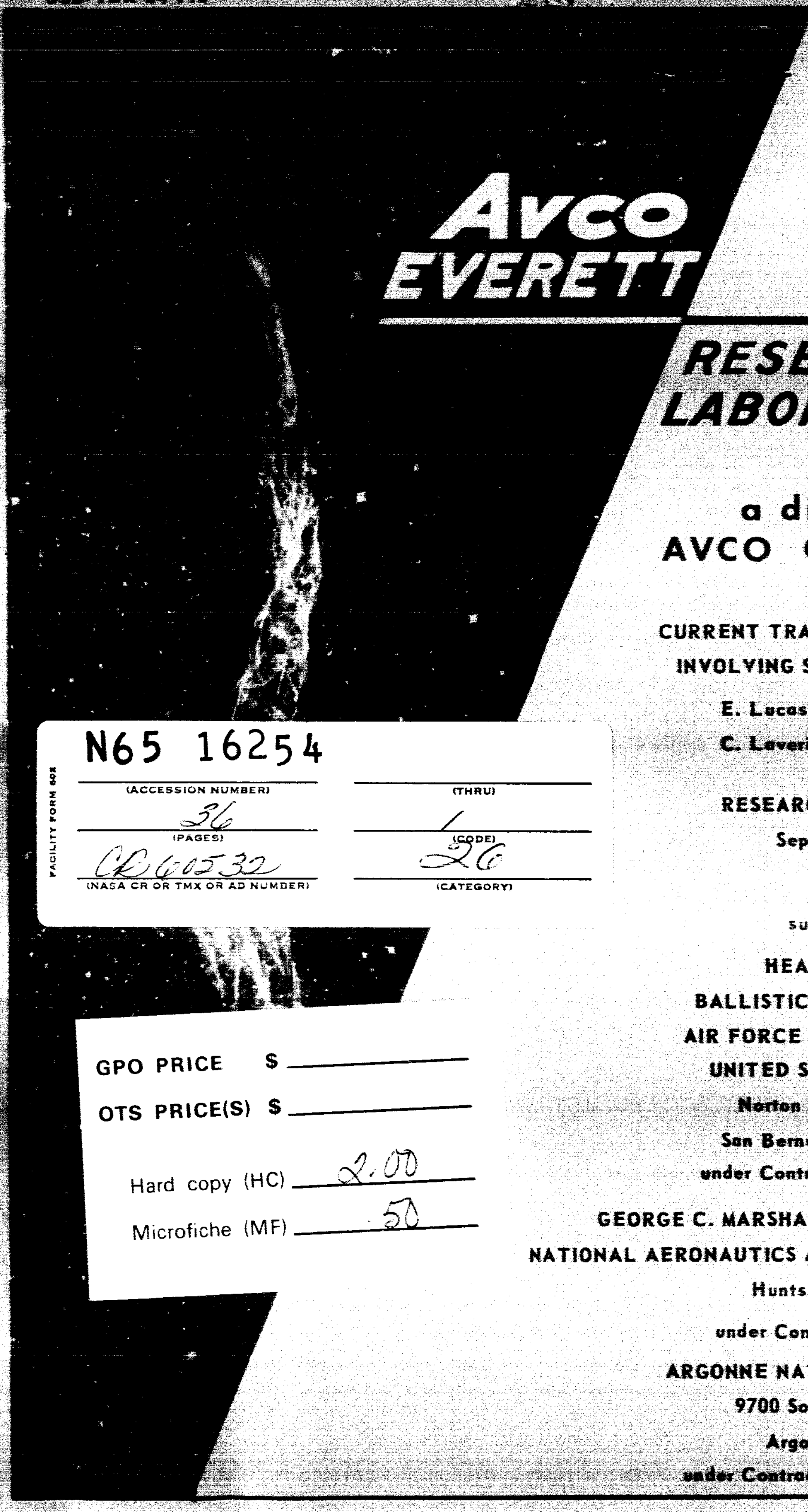
BSD-TDR-64-110



AVCO EVERETT RESEARCH LABORATORY

a division of
AVCO CORPORATION

CURRENT TRANSFER IN CONTACTS INVOLVING SUPERCONDUCTORS

E. Lucas, Z. J. J. Stekly,
C. Laverick and G. Pewitt

RESEARCH REPORT 193
September 1964

supported by

HEADQUARTERS
BALLISTIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Norton Air Force Base
San Bernardino, California
under Contract AF 04(694)-414

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Huntsville, Alabama
under Contract NAS 8-5279

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois
under Contract AEC 31-109-38-1498

BSD-TDR-64-110 RESEARCH REPORT 193

CURRENT TRANSFER IN CONTACTS INVOLVING SUPERCONDUCTORS

by

E. Lucas,* Z. J.J. Stekly,* C. Laverick** and G. Pewitt**

AVCO-EVERETT RESEARCH LABORATORY
a division of
AVCO CORPORATION
Everett, Massachusetts

September 1964

supported by

HEADQUARTERS
BALLISTIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Norton Air Force Base
San Bernardino, California

under Contract AF 04(694)-414

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Huntsville, Alabama

under Contract NAS 8-5279

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

under Contract AEC 31-109-38-1498

* Avco-Everett Research Laboratory, Everett, Massachusetts
** Argonne National Laboratory, Argonne, Illinois

Presented at

1964 Cryogenic Engineering Conference
University of Pennsylvania
August 18-21, 1964

ABSTRACT

16254

A theoretical analysis for the transfer of current between a power lead and a superconductor is given. This analysis assumes that a uniformly distributed surface resistivity exists between the superconductor and the normal conductor.

Experimental results with contacts between superconductors and power leads have been obtained during the course of experiments with short samples and small solenoids. These results are presented. The theoretical predictions have been checked experimentally and the results are given.

It is concluded that the maximum current which can be transferred through a joint, is a function of the following: (1) The magnitude and direction of the magnetic field at the joint; (2) the cooling of the joint; (3) the contact resistance. Joints should be located in low field regions and aligned parallel to the magnetic field. Reliability can be improved by paralleling joints. Crimped joints with indium coated wires and tubes are satisfactory for most applications.

Author

CURRENT TRANSFER IN CONTACTS INVOLVING SUPERCONDUCTORS

E. J. Lucas and Z. J. J. Stekly
Avco-Everett Research Laboratory, Everett, Massachusetts

and

C. Laverick and G. Pewitt
Argonne National Laboratory, Argonne, Illinois

INTRODUCTION

Joints between power leads and superconductors and between superconductors can be a source of error in experiments on superconductivity and of trouble and expense in superconducting magnets.

The following is a presentation of a theoretical and experimental program that was carried on to (1) develop a reliable contact that could be used in high field superconducting magnets, (2) analyze the mechanism whereby current is transferred to a superconductor, (3) establish design parameters that would permit comparative measurements to be made on various types of joints and (4) to establish a testing procedure for making such comparative measurements.

THEORETICAL ANALYSIS

Current Transfer

The transfer of current into a superconductor from a normal conductor in a contact can be idealized by the circuit shown in Fig. 1. In an actual contact the surface resistance may vary along the length of the contact, especially in one which is made by crimping the normal material around the superconductor at several points. For the purpose of this analysis it is assumed that an average uniformly distributed surface resistivity exists between the superconductor and the normal conductor.

Initially all the current is in the normal conductor. The transfer starts at the beginning of the contact between normal conductor and the superconductor. Let us assume initially that the temperatures are low enough so that the superconductor remains in its superconducting state with zero resistance throughout the length of the contact.

If we write the circuit equations for a length Δ x of the ladder network shown in Fig. 1, and then allow Δ x to approach zero, the equation for the current in the normal conductor is:

$$\frac{d^2 I_n}{dx^2} = \frac{I_n}{{x_s}^2} \tag{1}$$

where

$$x_s = \sqrt{\frac{S}{r}}$$

and the quantities r and S are defined as follows:

r = resistance per unit length of normal conductor [Ω/cm]

S = surface resistance of unit length of contact [Ω cm]

The boundary conditions are:

$I_n = I_o$ at $x = O$ and

$I_n = O$ at $x = \ell$

This results in an equation for the current in the normal conductor:

$$I_n = I_o \frac{\sinh \frac{\ell - x}{x_s}}{\sinh \frac{\ell}{x_s}} \tag{2}$$

and the current in the superconductor

$$I_S = I_o \left[1 - \frac{\sinh \dfrac{\ell - x}{x_s}}{\sinh \dfrac{\ell}{x_s}} \right] \tag{3}$$

The potential V of the normal material above the potential of the superconductor is given locally by the current flowing through the surface resistance:

$$V = -S \frac{d\, I_n}{dx} = \frac{S\, I_o}{x_s} \frac{\cosh\left(\dfrac{\ell - x}{x_s}\right)}{\sinh \dfrac{\ell}{x_s}} \tag{4}$$

The voltage at x = 0 divided by I_o represents the resistance of the contact:

$$R_c = \left.\frac{V}{I_o}\right]_{x = 0} = \frac{S}{x_s} \coth \frac{\ell}{x_s} = r\, x_s \coth \frac{\ell}{x_s} \tag{5}$$

The above expression for contact resistance is plotted in Fig. 2 and shows that for long contacts (ℓ/x_s large) the contact resistance is equal to the resistance of a length x_s of the normal conductor. For short contacts ($\ell/x_s < 1.0$) the contact resistance increases rapidly as ℓ/x_s decreases.

In some experiments the contact resistance has been measured using a potential difference at the end of the contact ($x = \ell$). The measured resistance for this case is:

$$R_\ell = \left.\frac{V}{I_o}\right]_{x = \ell} = \frac{S}{x_s \sinh \ell/x_s} = \frac{r\, x_s}{\sinh \dfrac{\ell}{x_s}} \tag{6}$$

This relationship is shown plotted in Fig. 2.

Measurement of R_ℓ is a measure of surface contact resistance for

$\ell/x_s < 1.0$ for $\ell/x_s > 1.0$, $R_\ell \rightarrow 0$ and a low value does not necessarily mean that a low surface resistance has been achieved.

Temperature Distribution

The current transfer characteristics of a contact are only one half of the overall picture, since failure of a contact results when the combination of current and temperature to which the superconductor is subjected is inconsistent with its being able to remain superconducting.

We shall consider two types of contacts of normal conductor to superconductor. The two contacts are shown idealized in Fig. 3.

(1) The first contact consists of a normal conductor which is exposed to helium up to the point where the superconducting-normal contact is made.

(2) The second one consists of a contact that is cooled for its entire length.

The temperature distribution for each case is calculated from the one dimensional heat conduction equation:

$$k\,A\,\frac{\partial^2 T}{\partial x^2} - h\,PT + \frac{\text{Joule heat generation}}{\text{unit length of contact}} = 0 \qquad (7)$$

In the above equation k is the thermal conductivity which, for simplicity, is assumed independent of temperature, A is the cross sectional area of the normal conductor, P is the cooled perimeter, h is the heat transfer coefficient.

For the Case I where the conductor is cooled only before contact is made with the superconductor:

for $x \leq 0$:

$$kA\,\frac{\partial^2 T}{\partial x^2} - h\,PT + r\,I_o^2 = 0 \qquad (8)$$

For the region where the current is transferring into the superconductor the heat generated per unit length is given by:

$$\frac{\text{Joule Heating}}{\text{Unit Length}} = r I_n^2 + S \left(\frac{d I_n}{dx} \right)^2 \tag{9}$$

the first term represents heat generated in the normal conductor and the second term heat generated in the surface resistance by the transfer of current from normal conductor to superconductor.

Substituting for I_n from Eq. 2 results in:

$$\frac{\text{Joule Heating}}{\text{Unit Length}} = r I_o^2 \frac{\cosh 2 \dfrac{\ell - x}{x_s}}{\left[\sinh \dfrac{\ell}{x_s} \right]^2} \tag{10}$$

For this contact we have assumed that the transfer of current takes plac in the insulated part of the contact, so the temperature distribution is given by:

$$kA \frac{\partial^2 T}{\partial x^2} + r I_o^2 \frac{\cosh 2 \dfrac{\ell - x}{x_s}}{\left[\sinh \dfrac{\ell}{x_s} \right]^2} = 0 \qquad x \geq 0 \tag{11}$$

Equations 8 and 11 together define the temperature distribution in the whole contact.

For simplicity we shall take the temperature T to represent the temperature rise above the cooling bath. The boundary conditions are then:

$$T \neq \infty \quad \text{at } x \longrightarrow -\infty$$

$$\frac{dT}{dx} = 0 \text{ at } x = \ell \quad \text{(no heat conducted out of the end longitudinally)}$$

$$T, \frac{dT}{dx} \quad \text{continuous at } x = 0$$

Using these boundary conditions together with equations 8 and 11:

$x \geq 0$

$$\frac{hPT}{rI_o^2} = 1 + \frac{x_s^2}{4x_o^2}\left[\frac{\cosh\frac{2\ell}{x_s} - \cosh 2\left(\frac{\ell - x}{x_s}\right)}{\left[\sinh\frac{\ell}{x_s}\right]^2}\right] + \frac{x_s}{x_o}\coth\frac{\ell}{x_s}$$

$x \leq 0$

$$\frac{hPT}{rI_o^2} = 1 + \frac{x_s}{x_o}\, e^{\frac{x}{x_o}} \coth\left(\frac{\ell}{x_s}\right) \tag{12}$$

where

$$x_o \equiv \sqrt{\frac{kA}{hP}}$$

Case II - For this case, the contact is cooled for its entire length and Eq. 11 is replaced by:

$x \geq 0$

$$kA\frac{d^2T}{dx^2} - hPT + rI_o^2\frac{\cosh 2\frac{\ell - x}{x_s}}{\left[\sinh \ell/x_s\right]^2} = 0 \tag{13}$$

while the temperature in the region $x \leq 0$ is still obtained from Eq. 8. The boundary conditions remain unchanged (we still neglect any heat transfer out the end of the contact, so $dT/dx = 0$ at $x = \ell$).

The results for the temperature distribution are:

$x \geq 0$

$$\frac{hPT}{rI_c^2} = e^{-\frac{\ell}{x_o}}\cosh\frac{\ell - x}{x_o}\left[1 - \frac{\cosh 2\frac{\ell}{x_s} + \frac{2x_o}{x_s}\sinh\frac{2\ell}{x_s}}{\left(1 - \frac{4x_o^2}{x_s^2}\right)\left[\sinh\frac{\ell}{x_s}\right]^2}\right]$$

$$+ \frac{\cosh 2 \left(\frac{\ell - x}{x_s} \right)}{\left(1 - \frac{4 x_o^2}{x_s^2} \right) \left[\sinh \frac{\ell}{x_s} \right]^2} \tag{14}$$

and

$x \leq 0$

$$\frac{h P T}{r I_o^2} = 1 + \left[e^{-\frac{\ell}{x_o}} \cosh \frac{\ell}{x_o} \left\{ 1 - \frac{\cosh 2 \frac{\ell}{x_s} + 2 \frac{x_o}{x_s} \sinh \frac{2\ell}{x_s}}{\left(1 - 4 \frac{x_o^2}{x_s^2} \right) \left[\sinh \frac{\ell}{x_s} \right]^2} \right\} \right.$$

$$\left. -1 + \frac{\cosh 2 \frac{\ell}{x_s}}{\left(1 - 4 \frac{x_o^2}{x_s^2} \right) \left[\sinh \frac{\ell}{s} \right]^2} \right] e^{\frac{x}{x_o}} \tag{15}$$

Results of Theoretical Analysis

The results of the theoretical analysis are best shown in graphical form. Figure 4 summarizes the details of the current transfer and temperature analysis for a contact of length $\ell = x_s$, and $x_s = 2.5\, x_o$.

The figure shows the current in the superconductor, current in the normal conductor, voltage in the normal conductor with reference to the superconductor, heating per unit length of contact, temperature distribution for the case of a contact with an insulated section in the region of the superconducting wire, and for the case where it is cooled for its entire length.

The heat generation per unit length requires a comment at this point. Until current transfer begins, the heat generation is merely the joule heating in the normal conductor. However, when the transfer of current begins, additional heating occurs at the interface between the normal conductor and the superconductor. Since the current in the normal conductor is still very close to its initial value, an increase in heat generation occurs.

For a contact which is insulated in the region of current transfer, the maximum temperature occurs at the end of the contact ($x = \ell$) where the superconductor is required to carry the full current I_o flowing through the contact. From Eq. 12 the temperature at this point is:

$$\frac{h P T_e}{r I_o^2} = 1 + \frac{1}{2} \left(\frac{x_s}{x_o} \right)^2 \frac{x_s}{x_o} \coth \frac{\ell}{x_s} \qquad (16)$$

Note that the temperature rise T_e drops as ℓ increases.

If the temperature T_e is such that the superconductor cannot carry the current I_o, then the superconductor becomes resistive.

In general, under a given set of conditions we can define a temperature rise above the cooling bath T_c which will make the superconductor resistive; also let us define a current I_c which can be passed through the superconductor while it is at the bath temperature. The current which can be passed through the superconductor I_o is a function of its temperature T, and falls from I_c at $T = 0$ to zero at $T = T_c$. As an approximation let us assume that this decrease in current carrying capacity is linear.

$$\frac{I_o}{I_c} = 1 - \frac{T}{T_c} \qquad (17)$$

Using this relationship between current I_o and temperature T as well as Eq. 16 for the maximum temperature in the contact results in:

$$\frac{1 - \frac{I_o}{I_c}}{\left(\frac{I_o}{I_c}\right)^2} \geq \frac{r\, I_c^{\,2}}{h\, P\, T_c}\left(1 + \frac{1}{2} \; \frac{x_s^{\,2}}{x_o^{\,2}} + \frac{x_s}{x_o} \coth \frac{\ell}{x_s}\right) \qquad (18)$$

The inequality denotes the values of the expression on the right for the superconductor in the contact to remain superconducting up to a fraction I_o/I_c of the current it could carry if it were truly at the temperature of the surrounding bath.

For case II, where the contact is cooled for its entire length, the maximum temperature occurs near the beginning of the contact, where the current has not yet fully transferred into the superconductor. From the temperature distribution in Eq. 14, and using Eq. 17 the allowable current in the superconductor can be obtained:

$$\left(\frac{hPT_c}{r\, I_c^{\,2}}\right)\frac{I_c^{\,2}}{I_o^{\,2}}\left(1 - \frac{I_a}{I_c}\right) = e^{-\frac{\ell}{x_o}} \cosh \frac{\ell - x}{x_o}$$

$$\left[1 - \frac{\cosh \frac{2\ell}{x_s} + \frac{2\, x_o}{x_s} \sinh \frac{2\ell}{x_s}}{\left(1 - 4\frac{x_o^{\,2}}{x_s^{\,2}}\right)\left[\sinh \frac{\ell}{x_s}\right]^2}\right] + \frac{\cosh 2\left(\frac{\ell - x}{x_s}\right)}{\left(1 - 4\frac{x_o^{\,2}}{x_s^{\,2}}\right)\left[\sinh \frac{\ell}{x_s}\right]^2} \qquad (19)$$

The actual current flowing in the superconductor at any point is given by Eq. 3 and varies along the length of the contact.

When the allowable current I_a, at any point becomes equal to the current I, the limiting condition is reached and any further increase in current through the contact makes the superconductor resistive.

In designing a contact Case 1 results in an expression (Eq. 18) which is relatively easy to use. The case II solution clearly shows that the temperatures are reduced from those of case I and therefore contacts which satisfy Eq. 18 will have an additional safety factor if they are cooled over their whole length.

To see the effect of the individual variables on the contact performance we can write Eq. (18) in terms of primary quantities:

$$\frac{1 - \frac{I_o}{I_c}}{\left(\frac{I_o}{I_c}\right)^2} \geq \frac{r I_c^2}{h P T_c} + \frac{1}{2} \frac{S I_c^2}{k A T_c} + \sqrt{\frac{Sr}{h P k A}} \frac{I_c^2}{T_c} \coth \ell \sqrt{\frac{r}{S}} \tag{20}$$

For values of I_o/I_c close to unity the left hand side of the equation becomes merely $1 - I_o/I_c$. From the above it is clear that a good contact has the following characteristics:

1. High thermal and electrical conductivity in the normal conductor.
2. Low surface resistance
3. A contact length longer than $\sqrt{\frac{S}{r}}$
4. Good cooling as far as exposing the surface to the bath, as well as good thermal contact between the superconductor and the normal conductor.
5. High T_c obtained by placing contact in region of low field.
6. For a given I_o, we would like high I_c which is obtainable by placing the superconductor parallel to the magnetic field.

It is important to point out that the limitation on the contact is a thermal one, and that having a low resistivity alone does not insure good contact performance.

The onset of resistance in a contact may be catastrophic or gradual depending on the cooling available. Onset of resistance in the superconductor results in a new current distribution, with a new distribution of joule and surface heating. It is conceivable that the temperature distribution could readjust to a new stable situation resulting in a higher resistance in the contact, but not a catastrophic propagation of the resistive region. It is expected that this increase in contact resistance would be catastrophic in the case where the current transfer section is insulated, because the highest temperature occurs at the point where the superconductor is required to carry the most current. Once this point becomes resistive, an unstable situation will probably result.

If the contact is cooled for its full length the appearance of resistance occurs at a point in the contact where the superconductor doesn't have to carry the full current, so that a new stable situation with a higher contact resistance is possible.

EXPERIMENTAL INVESTIGATIONS

Introduction

Experimental investigations were carried on with two objectives in mind. The first objective was to test the predictions of the theoretical analysis presented in the previous section and to subsequently establish a testing procedure which would permit a quantitative comparison of the various methods of transferring current to superconducting wires. The second objective was to develop a contact which could reliably be used in superconducting magnets requiring energizing currents up to 35 amperes.

Experiments to Test Theoretical Predictions

Two groups of experiments were run to check out the theoretical predictions of this paper. The first group involved the use of contacts that were longer than x_s, while the second group involved the use of contacts that were shorter or at most comparable to x_s.

Six samples were made for the first group of experiments. These samples were all approximately twenty inches long and had a contact length of approximately sixteen inches. All of the contacts made use of OFHC copper tubing having an outside diameter of 1/8 inch and an inside diameter of .030". In each case the superconductor was a .010" outside diameter Nb-33% Zr wire.

The contacts were made by cleaning the copper tubes with a non-acid flux, inserting the superconducting wire along with some filler wires into the tube, and then collapsing the walls of the tube around the wires with a crimping tool.

Two types of crimping tools were used. The first consisted of a set of diamond shaped dies that were brought together around the contact by means of a hydraulic press, while the second was a hand-operated Stakon (type T and B) tool.

Voltage taps were placed along the length of the contact. These taps were placed at one inch intervals except in the two inch length bracketing the start of the contact where they were placed at 1/4 inch intervals. These taps were attached to the copper tube with high purity indium solder. Power was transferred to the copper tube from an external lead by soldering the lead to the tube with a 50% tin-50% lead soft solder.

A detailed description of each of the samples is given in Appendix 1.

Testing of each of the samples was accomplished by immersing the contact in liquid helium and exciting it with currents of 30, 50 and 70 amperes. Voltage measurements were then read at each of the taps with the superconducting wire serving as the reference. The contacts were tested in pairs so that the excitation current transferred through one contact to the superconductor and then from the superconductor to the second contact. Reversing the excitation leads made no difference in the magnitude of voltages read.

Figure 5 is a plot of volts/amperes versus distance from the contact end for sample No. 2. This curve is typical of those that were obtained for the other five samples. Table one is a summary of the contact characteristics that were obtained from the samples tested in this group.

Table 1

Sample No.	x_s (cm.)	r (Ω/cm x 10^7)	S (Ω cm x 10^7)
1	.645	3.03	1.26
2	.762	2.44	1.42
3	1.27	2.70	4.35
4	1.52	2.46	5.70
5	1.52	3.02	7.00
6	1.14	2.44	3.04

The second group of samples tested were constructed in a manner identical to sample #3 in the first group except that their conductor contact lengths were 1 inch, 1/2 inch and 1/4 inch respectively and the voltage taps were placed at 1/8 inch intervals in the vicinity of the start of the contact between the superconductor and the normal conductor.

These samples were tested in the same fashion as the first group except that the tests were repeated in and out of magnetic fields.

Figure 6 is a plot of the volts/amperes versus distance from the contact end for each of these three contacts in zero magnetic field. Again the superconducting wire was used as the reference point for those measurements. Figure 6 shows the variation of the voltage distribution as the length is changed. Theory predicts that the resistance R_c should decrease with increasing length, yet R_c for the 1/2-inch length is less than for the 1-inch length. It is expected that this is due to a variation of the surface contact resistance where a better surface resistivity has been achieved in the 1/2-inch contact.

Table 2 is a summary of the contact characteristics that were obtained by making use of the measurements made on these tests and the x_s obtained from sample #3 of the first group.

Table 2

Sample #	r (Ω/cm x 10^7)	R_c (Ω x 10^8)	ℓ (cm)	R_ℓ (Ω x 10^8)	$\frac{R_c}{r x_s}$	External Field (Kg)
7	2.64	31	2.54	12	.93	0
7	2.94	36	2.54	11	.97	30
7	3.63	39	2.54	12	.85	50
8	2.49	27	1.27	15	.86	0
8	2.7	33	1.27	12	.96	30
8	3.14	50	1.27	22	1.25	50
9	2.76	105	.635	90	3.0	0
9	3.82	150	.635	124	3.1	50

(x_s = 1.27 cm was assumed to be equal to that of sample 3 which was made the same way as samples 7 to 9.)

In the tests involving sample #7 the magnetic field was parallel to the long dimension of the contact, while in the tests involving samples 8 and 9 it was perpendicular to the long dimensions of the contacts.

Figure 7 is a replot of the theoretical curve for R_c shown in Fig. 2 with the points obtained for samples 7, 8 and 9 superimposed. The three points shown for samples 7 and 8 and the two shown for sample 9 are the value of $R_c/r\,x_s$ that were obtained at the various magnetic field intensities. The x_s used was that value obtained from sample 3. The data of all reasonably close to the theoretical predictions and their departure from the theoretical curve represents the accuracy with which quantitative predictions can be made on contacts based on data gathered on a long contact made in the same way.

CONTACTS FOR CURRENTS UP TO 35 AMPERES

Two types of contacts are usually required in superconducting magnets. These contacts are: (1) contacts between power leads and the superconducting wires at the ends of the coil and (2) contacts between the superconducting wires themselves.

The purpose of this portion of the program was to develop normal conductor to superconductor and a superconductor to superconductor contacts that could reliably be used in superconducting magnets that required excitation currents up to 35 amperes. A wide variety of contacts were tested to ascertain suitability for use in this application as determined by: (1) their current carrying capacities in and out of magnetic fields, (2) the repeatability of their characteristics in a large number of contacts and (3) the techniques that must be used to make these contacts in a superconducting magnet.

The contact making techniques that were tried include the following: copper clamps in which the superconducting wires are clamped between indium coated copper plates, crimps in which the superconducting wire is crimped inside a copper or silver tube using either a hand or a hydraulic powered crimping tool, welds, soldered contacts, and pressure contacts where two superconducting wires are squeezed together in a grooved bulk superconductor. In each case, except for the soldered connections, the best results were obtained when the superconductors were cleaned and etched before the contact was made.

A resistance of one micro ohm measured at an excitation current of 35 amperes was established as a performance check in evaluating contacts that would be considered acceptable. This resistance value was chosen since experience had shown that contacts of this quality were rarely detected to be the origin of normal regions in superconducting magnets.

The following is a listing of the contacts that were tried together with a brief description of the contacts themselves and some of the results of the tests that were conducted:

Clamped Contacts

Table 3 is a listing of the performance that was obtained by clamping etched superconducting wires between plates. Sample #10 was made by clamping a power lead to one side of an indium coated washer and a spiral of etched superconducting wire by means of a stainless steel nut and bolt. Sample #11 was made by clamping an etched superconducting wire between a 1/2 inch square copper washer and a 2" by 1" rectangular copper plate. Sample #12 was made by clamping an etched superconductor between a copper plate 1" long by 1/2" wide and a second copper plate 2" long by 1" wide.

Table 3

Resistance and Zero Field Quenching

Currents for Clamped Contacts

Sample No.	Quench Current (amperes)	Maximum Contact Resistance ($\Omega \times 10^6$)
10	95	2.6
11	52	19.4
12	67	148

Crimped Contacts

A large number of crimped contacts* were made both for transferring current from a normal conductor to a superconductor and from superconductor to superconductor. These contacts made use of either silver or copper tubing having an outside diameter of 1/8" and an internal diameter of .030". The bores of these tubes were either cleaned and etched or ultrasonically coated with pure indium. The lengths of the contacts were varied from 1/2 inch up to several inches with the longer contacts consistently exhibiting the lower resistance values.

A reliable normal to superconducting contact was made by making use of a 2-1/2 inch long copper tube indium tinned with four superconducting indium coated leads placed in the bore. Three of the leads acted as fillers while the fourth was the conductor. The normal conductor was soldered to the tubing after the superconducting wires were in place, however, a great deal of care was taken to keep the heat generated during this process from melting the indium coating of the tube.

*This type of contact was first used by R. Boom, Atomics International

A reliable superconductor to superconductor contact was made by inserting two indium coated conductors together with two filler leads into a 3/4" indium coated tube and crimping.

Both the normal to superconductor and superconductor to superconductor joints described above were tested in fields up to thirty kilogauss and exhibited resistances lower than one micro ohm at currents of 25 amperes. Contacts identical to those above but shorter in length generally exhibited higher resistances when subjected to a similar test.

Table 4 is a listing of typical resistance values for several contacts in series that were made as described above,* while Fig. 8 shows H-I curves for one of these samples taken with the field parallel and perpendicular to the direction of current flow in the conductors. These curves are typical of those taken for the contacts described above.

These curves clearly illustrate the advantages of orienting joints parallel to the field whenever possible.

Table 4

Contact Resistance of Several Crimp-Type Contacts in Series

Specimen No.	Contact Length	Total Resistance of Contacts ($\Omega \times 10^6$)	Remarks
13	3/4"	.25	2 N-S* plus 2 S-S**
14	1/2"	1.3	2 N-S plus 4 S-S
15	1/2"	2.5	
16	1/2"	.4	

*Detailed descriptions are presented in Appendix II.
**N-S = normal to superconductor contact
S-S = superconductor to superconductor contact

Pressure Type Contacts

These contacts were used only to connect superconductors to superconductors. They consisted of a copper block with a niobium-zirconium insert grooved to accept two .010" wires. A stainless steel cap was used to press both wires together in the block. These contacts were extremely effective when used in small numbers, however, when used in large quantities, a high degree of quality control is needed to assure consistent performance. To alleviate this burden, the blocks were backed up with the 3/4" crimp type contact described. This dual type contact proved to be very effective.

Table 5 is a listing of typical resistance values for the dual type contacts. These resistances were taken with the conductors perpendicular to the field and at a current of 35 amperes.

Table 5

Resistances for Block Type Contacts in Parallel with Crimp Type Contacts

Sample No.	Sample Current (amperes)	Resistance in a field of 35 Kg. ($\Omega \times 10^6$)
17	35	.03
18	35	.035
19	35	.046
20	35	.017
21	35	.12
22	35	1.0

Resistance Welded Contacts

The performance of resistance welded superconducting contacts was studied using a range of welding pressures and energies known to give satisfactory mechanical joints. A comparison of the performance of welded contacts against the performance of the superconducting wire itself shows that there was considerable degradation for the welds studied. A significant point noted was that the resistance of the weld was immeasurably low while the contact was superconducting. This, of course, means that it is necessary to stipulate more than resistance when specifying a superconducting contact.

More work seems to be needed on welds. Our conclusions were that they, while not suitable for use in large magnets, where contacts may be located in high field regions, they could be used on smaller magnets where they could be located in a low field region. Lower welding energies yielded higher H-I curves, although as the energy was decreased, the weld became structurally weaker. Orientation of the weld in the field did not seem to affect its performance.

Soldered Contacts

Soft soldered contacts can be made with superconducting cables or braids if the individual strands of the conductor are copper coated and a good bond exists between this coating and the superconductor. Contacts made in this fashion carried currents in excess of 350 amperes in six and seven stranded cables.

The Effect of Contact Resistances on Coil Performance

Table 6 is a listing of the maximum coil currents and contact resistances that were obtained for several small coils. This data shows that coil performance can seriously be impaired by a defective contact. A decrease in contact resistance from 40 $\mu\Omega$ to 1 $\mu\Omega$ at low fields usually causes a large increase in coil quenching current. Thermal transitions in Nb-Zr wire were initiated by the dissipation of as little as 3 milliwatts of power at the contact. Decreases in contact resistances below 12 micro ohms did not seem to lead to increases in coil quenching currents. Contact resistances above 12 micro ohms affected coil performance although some short samples have operated up to 200 amperes with 200 micro ohm contacts. These higher resistance contacts had very large cooling areas.

Table 6

Maximum Quenching Currents and Contact Resistances for a Series of Coils

	Test 1		Test 2	
Coil No.	Max. Current (amperes)	Max. Contact Resistance ($\Omega \times 10^6$)	Max. Current (amperes)	Max. Contact Resistance ($\Omega \times 10^6$)
1	23.4	1250	32.5	6.8
2	17	46	51	0.2
3	28	1	26	1.5
4	8	40	29.6	1
5	10	72	26.2	1
6	10	400	30	.66

CONCLUSIONS

Both the analytical and experimental results indicate that the performance of a superconducting joint is strongly dependent upon the following factors: (1) the thermal environment; (2) the magnitude of resistivity that exists between the conductors; (3) the length of the contact and (4) the orientation of the contact in the magnetic field.

Superior performance was always obtained when contacts were lengthened, placed parallel to the magnetic field and placed in direct contact with liquid helium.

ACKNOWLEDGMENT

This work was performed at the Avco-Everett Research Laboratory and the Argonne National Laboratory and was supported by the following contracts: Ballistic Systems Division under Contract AF 04(694)-414, NASA under Contract NAS 8-5279 and AEC under Contract 31-109-38-1498.

APPENDIX I

The following is a list of the various long samples that were used to test the theoretical predictions of this paper together with a description of the construction details of each of these samples.

Sample #1 - This sample was made by inserting four copper coated .010" Nb-33% Zr wires into a 1/8 inch O.D. .030" I.D. OFHC copper tube. Three of the superconducting wires were used as filler while the fourth was used as the conductor. All of the superconducting wires were copper coated with a thickness of .00075 inches. This coating was sanded lightly before the wires were inserted into the tube. All wires were inserted 16 inches into the tube which was approximately 20 inches long. The three filler wires were cut off at the end of the tube while the fourth wire was inserted into a second copper tube separated from the first tube by a wire length of approximately 10 inches. The copper tube was crimped for its entire length with a diamond shaped die by means of a hydraulic press.

A number 14 stranded wire was soft soldered to the copper tubes with a 50% lead, 50% tin solder. This lead was attached at the end of the tube away from the end into which the superconducting wires were inserted. It was soldered to the tube over an approximate length of two inches. This soldering was done after the tube had been crimped.

Voltage taps were soldered to the copper tube with high purity indium solder.

Sample #2 - This sample was constructed in the same fashion as sample #1 except that it was hand crimped with a Stakon type T and B tool. Adjacent crimps were made at less than 1/8 inch intervals and at 90^{o} from one another.

Sample #3 - This sample was constructed in the same fashion as sample #1 except that two .010" copper wires were used as filler in place of the Nb-33% Zr wires.

Sample #4 - This sample was constructed in the same fashion as sample #3 except that the crimping was done in the same manner as in sample #2.

Sample #5 - This sample was constructed in the same fashion as sample #3 except that the copper coating was stripped from the superconducting wire and the wire was then ultrasonically coated with high purity indium.

Sample #6 - This sample was constructed in the same fashion as sample #5 except that it was crimped in the same manner as sample #2.

APPENDIX II

The specimens listed in Table 4 were composed of several contacts. A description of each specimen is given below. The resistance measurements listed in the table were taken across the entire specimen.

Specimen 13 consisted of two power contacts and two superconducting contacts connected in series. The series resistance of the two superconducting contacts was less than .2 micro ohms.

Specimens 14, 15 and 16 consisted of two power contacts and four superconducting contacts in series. The series resistance of the four superconducting contacts was .7 micro ohms, 1.5 micro ohms and less than .2 micro ohms for specimens 14, 15 and 16 respectively.

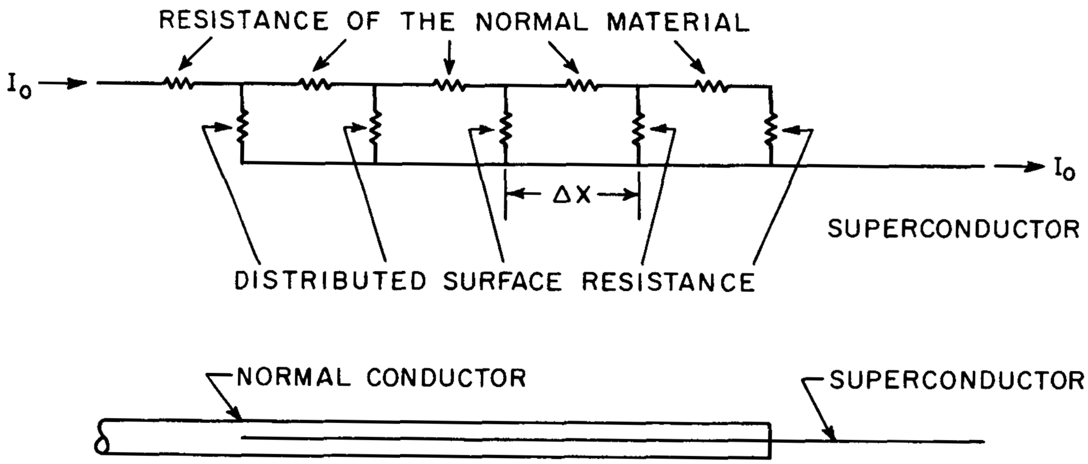


Fig. 1 Idealized circuit diagram for the transfer of current from a normal conductor.

A2292

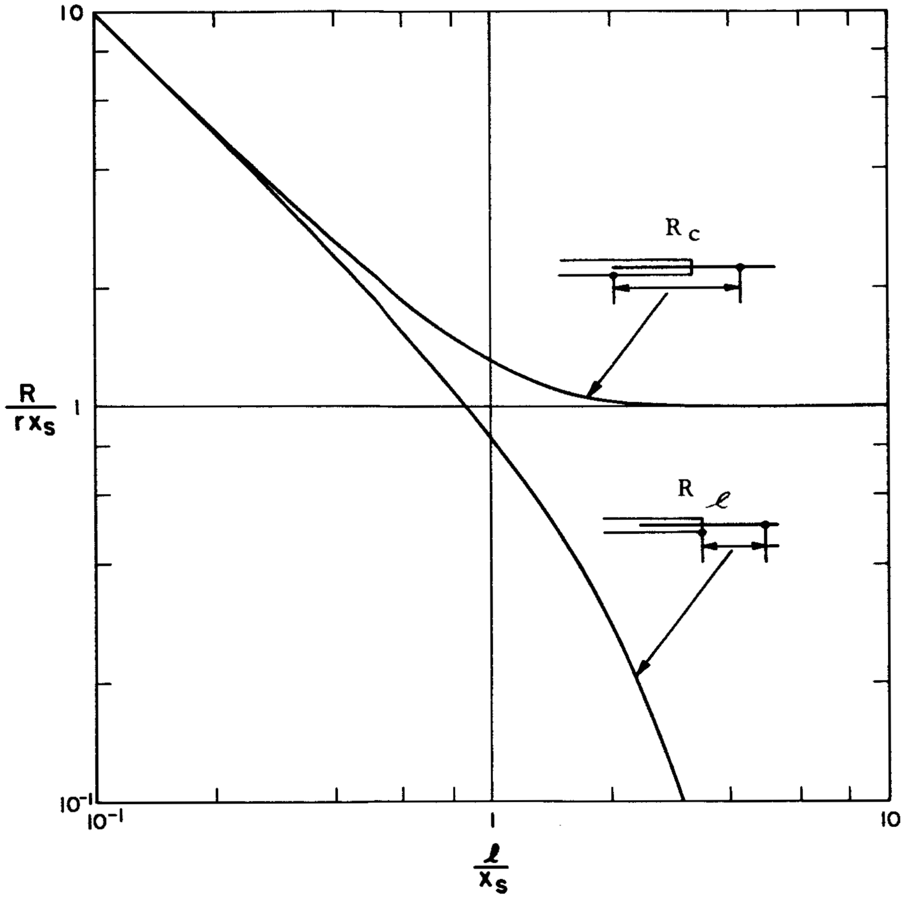


Fig. 2 The resistance of a contact as measured by (a) potential taps at the beginning of the contact and the superconductor (R_c) and (b) potential taps at the end of the normal conductor and the superconductor (R_ℓ). Both are shown plotted versus the length of the contact ℓ divided by the characteristic transfer distance x_s.

A2294

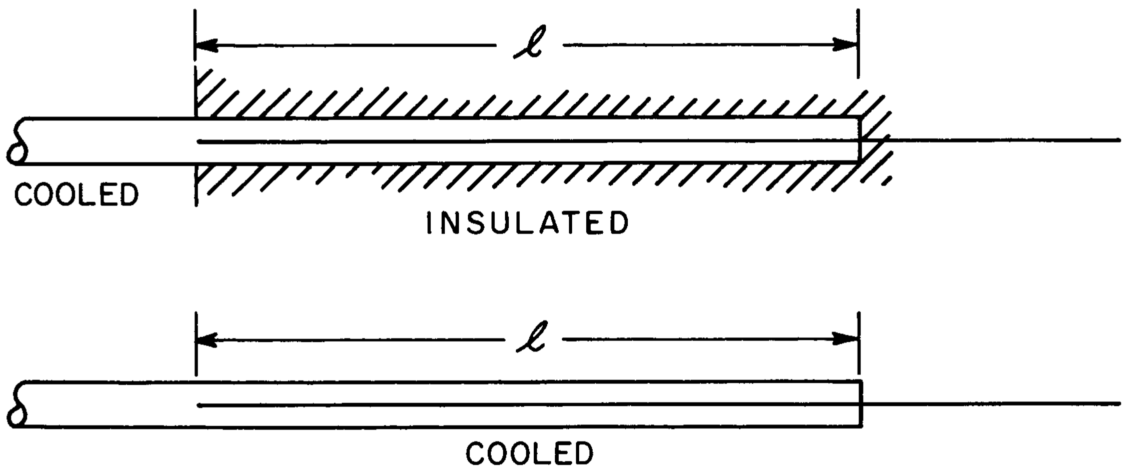


Fig. 3 Two idealized normal to superconductor contacts. The upper contact consists of a normal conductor which is exposed to helium up to the point where the contact starts, the lower contact is exposed to helium for its entire length.

A2291

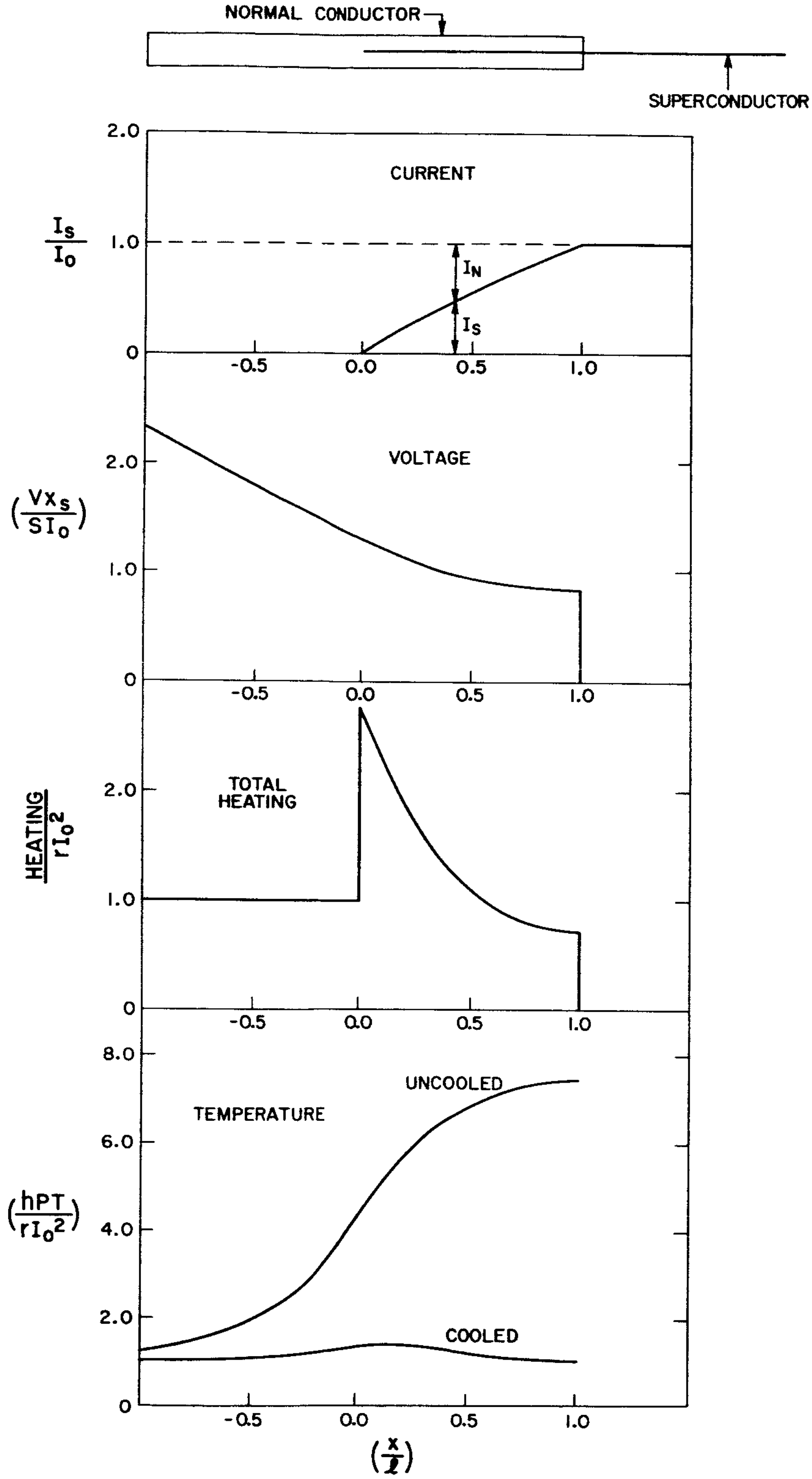


Fig. 4 This figure shows the theoretical variation of the current in the normal conductor, current in the superconductor, potential variation, total heating, and temperature distribution for cooled and uncooled contacts as a function of distance. The plots are made for $\ell = x_s$ and $x_s = 2.5\ x_o$.

A2293

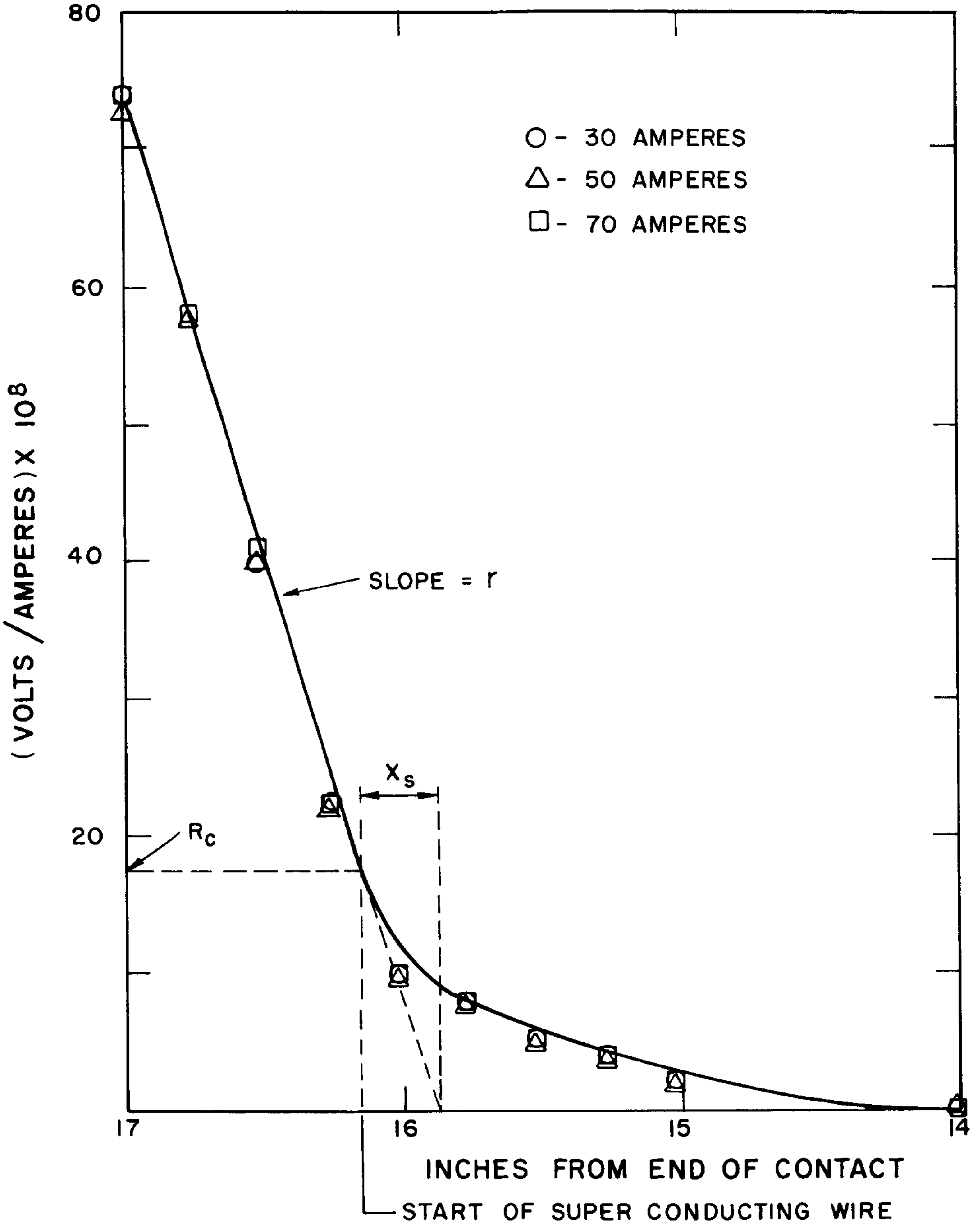


Fig. 5 Voltage divided by current for a typical long contact.

A2677

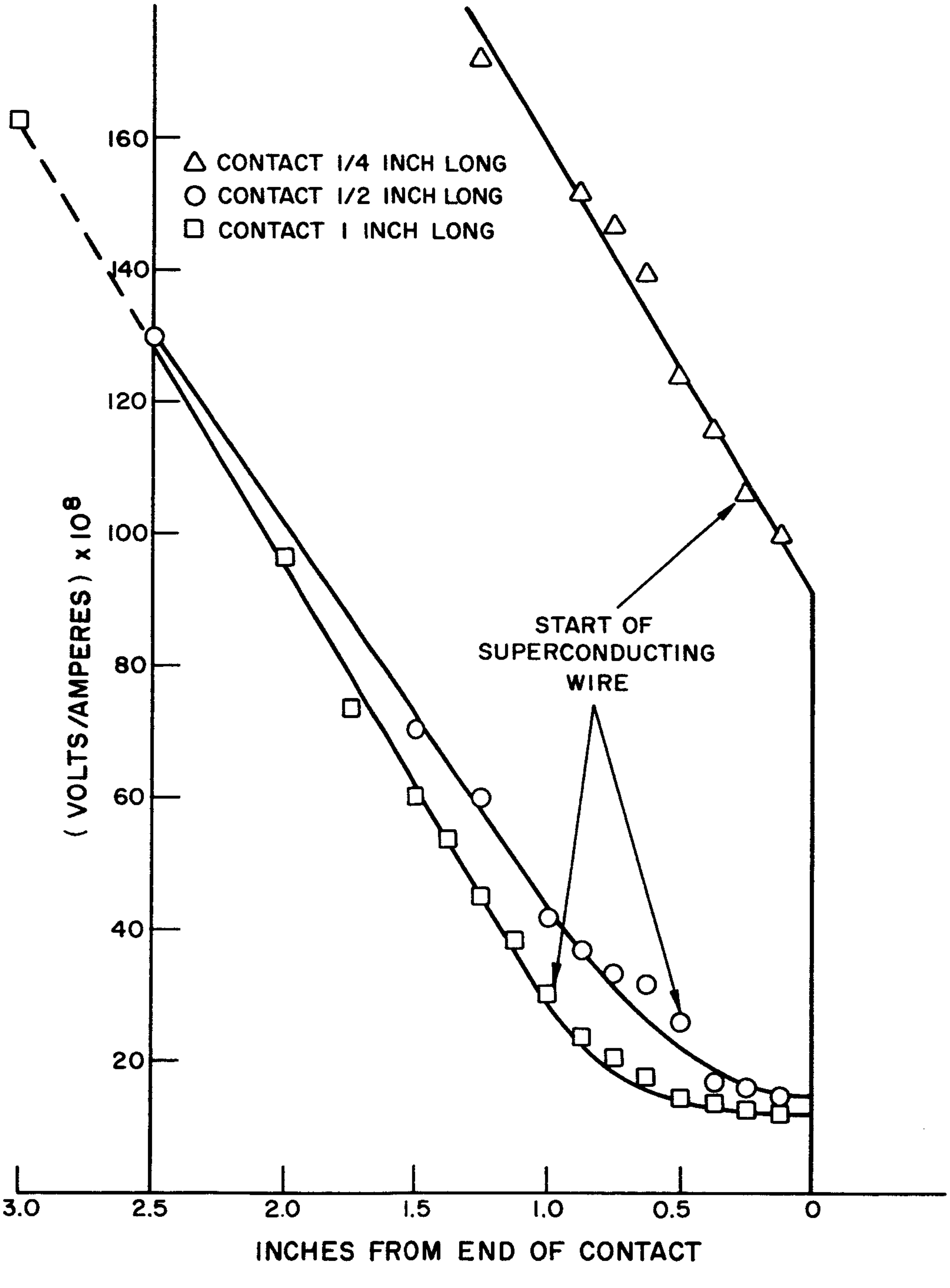
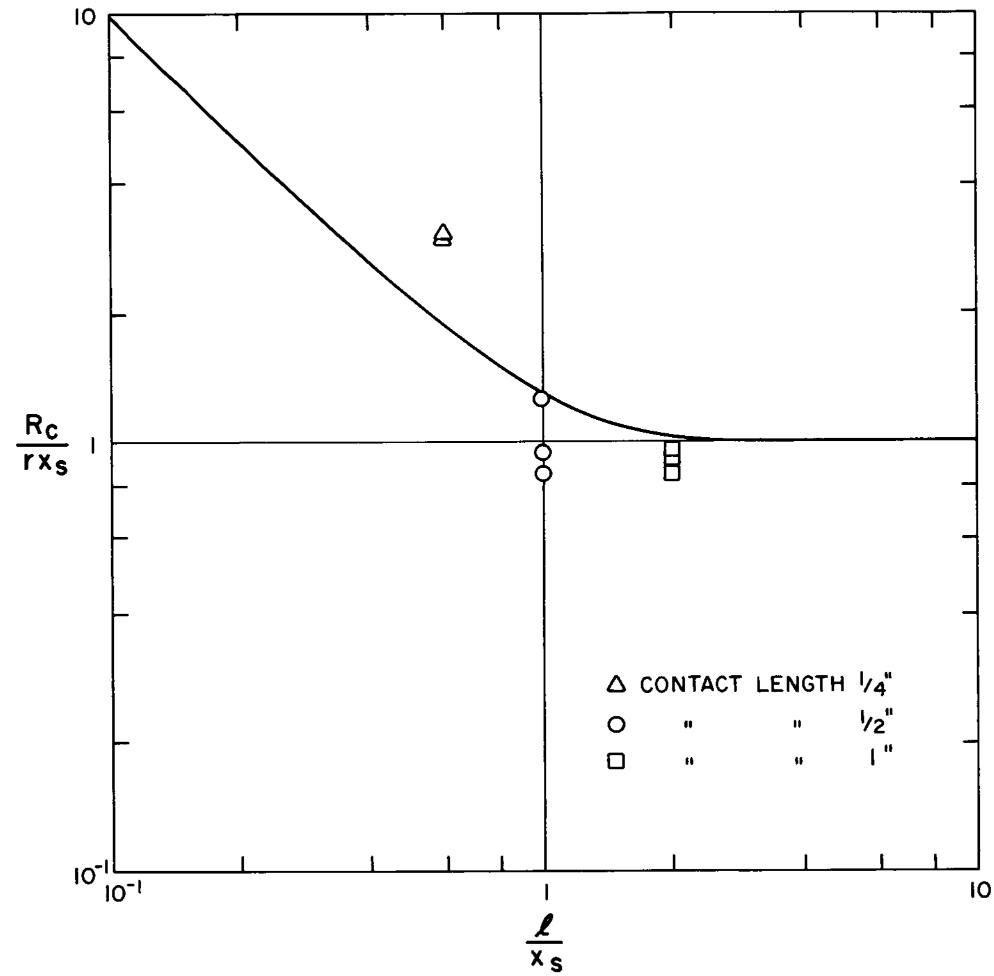


Fig. 6 Voltage divided by current for short contacts.

A2674



7 Comparison of measured values of R_c/rx_s versus ℓ/x_s to theoretical values for the same quantities.

A2675

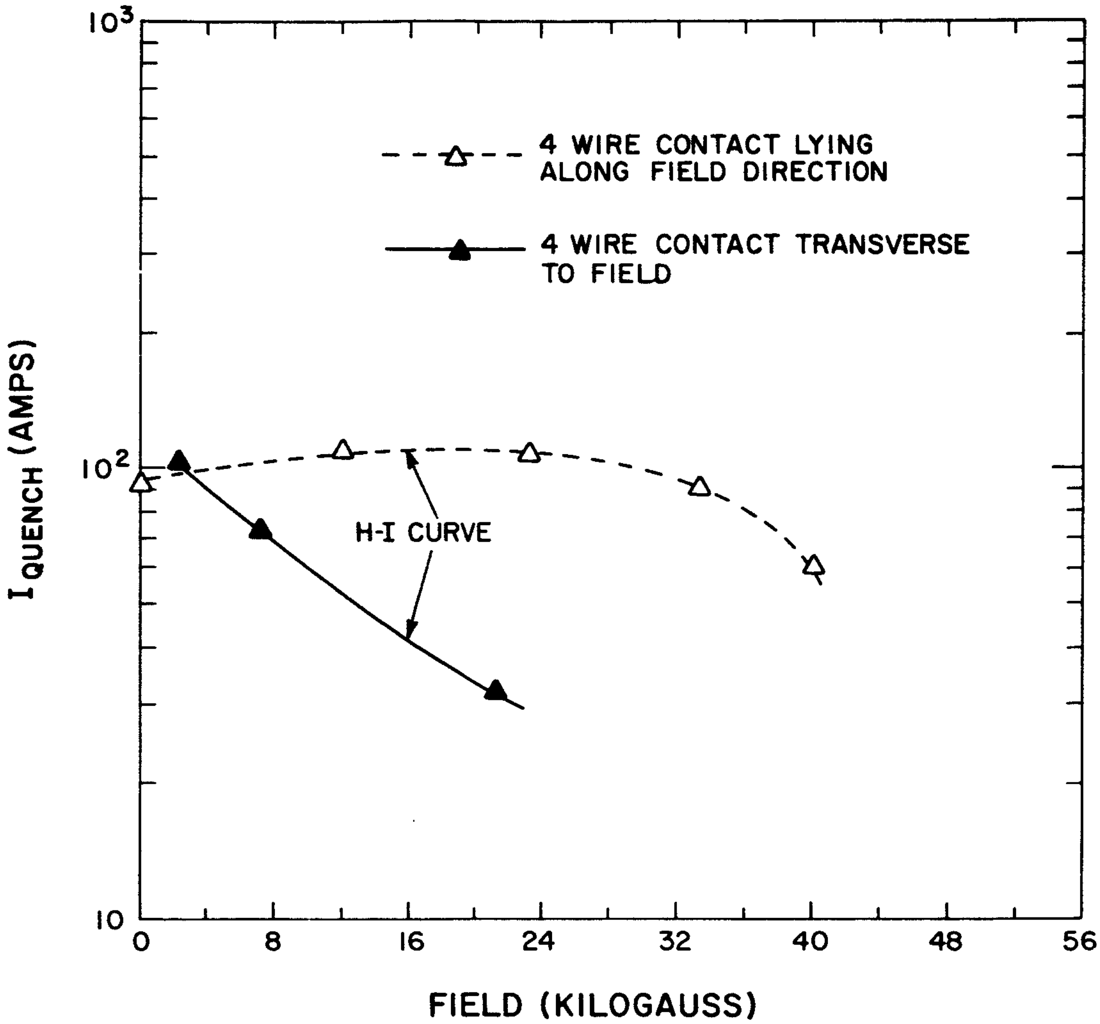


Fig. 8 Quench current versus magnetic field for four, 4-wire contacts in series.

A2676

DISTRIBUTION LIST for Contract No. AF 04(694)-414

Director, Advanced Research Projects Agency, Department of Defense, The Pentagon, 2B257, Washington 25, D.C.
Attn: Fred A. Keother (1 copy)
C. E. McLain (1 copy)
Mr. Hertzfeld (1 copy)

Defense Research Laboratories, General Motors Corporation, Santa Barbara, California - Attn: Cam Scharr (1 copy)

Headquarters Ballsitic Systems Division, Air Force Systems Command, Norton AFB, California - Attn: BSYDF (Lt. Jefferson) (2 copies)
BSTA (1 copy)

Air Force Cambridge Research Labs., Laurence G. Hanscom Field, Bedford, Massachusetts - Attn: Lew Block (1 copy)

Aerospace Corporation, Post Office Box 1308, San Bernardino, California - Attn: Paul Doherty (40 copies)

Systems Engineering Group (SEPIR), Wright-Patterson Air Force Base, Ohio 45433

Arnold Engineering Development Center, Arnold Air Force Station, Tennessee - Attn: AEYD (1 copy)
AES (1 copy)

MIT Lincoln Laboratories, Post Office Box 4188, San Bernardino, California - Attn: J. Vernon (1 copy)

U. S. Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, New Mexico - Attn: SWOIC (1 copy)
WLAX (1 copy)

Defense Documentation Center, Cameron Station, Alexandria, Virginia - (20 copies)

General Electric Company, Missile and Space Division, 3198 Chestnut Street, Philadelphia, Pennsylvania - Attn: J. Persh (1 copy)

General Electric Company, Valley Forge Space Technology Center, Space Sciences Laboratory, Post Office Box 8555, Philadelphia 1, Pa.
Attn: Lawrence I. Chasen, Manager
MSD Library (2 copies)

Headquarters U.S. Army Missile Command, Redstone Arsenal, Alabama - Attn: A. Jenkins (AMSMI-RRX) (1 copy)

Massachusetts Institute of Technology, Lincoln Laboratory, Post Office Box 73, Lexington 73, Massachusetts -
Attn: G.B. Pippert (1 copy)
Mary A. Granese,
Document Librarian (1 copy)
Dr. Ellen Bressel (1 copy)
Dr. Frank McNamara (1 copy)

University of Michigan, Institute of Sciences and Technology, Post Office Box 618, Ann Arbor, Michigan - Attn: Infrared Information and
Analysis Group (1 copy)
BAMIRAC Library (1 copy)
Richard Jamron (1 copy)

U. S. Atomic Energy Commission, Washington 25, D.C. - Attn: Headquarters Library (1 copy)

U. S. Atomic Energy Commission, Division of Technical Information Extension, Post Office Box 62, Oak Ridge, Tennessee - (1 copy)

Polytechnic Institute of Brooklyn Aero. Lab., 527 Atlantic Ave., Freeport, N.Y., 11520 (1 copy) New York - Attn: Prof. Martin Bloom
(1 copy)

Heliodyne Corporation, 2365 Westwood Boulevard, Los Angeles 64, California - Attn: Dr. Saul Feldman (1 copy)

Hughes Aircraft Company, Groud Systems Group, Fullerton, California - Attn: Library, Bldg. 600 (1 copy)

Hughes Aircraft Company, Florence and Teale, Culver City, California - Attn: Mr. Nicholas E. Devereau, Technical Document Center
(1 copy)

The Mitre Corporation, Post Office Box 208, Bedford, Massachusetts - Attn: Library (1 copy)

Plasmadyne Corporation, 3829 South Main Street, Santa Ana, California - Attn: Document Control (1 copy)

Aeronautical Research Associates of Princeton, Inc., 50 Washington Road, Princeton, New Jersey - Attn: Dr. Coleman deP. Donaldson (1 copy)

Sandia Corporation, Livermore Laboratory, Post Office Box 969, Livermore, California - Attn: Technical Library (1 copy)

Stanford Research Institute, Menlo Park, California - Attn: Acquisitions (1 copy)

Bendix Corporation, Bendix Products Division, 3300 West Sample Street, South Bend, Indiana - Attn: M. Katz (1 copy)

Bendix Corporation, Bendix Systems Division, 3300 Plymouth Road, Ann Arbor, Michigan - Attn: Library (1 copy)

The Boeing Company, Aerospace Division, P.O. Box 3707, Seattle 24, Washington - Attn: Library Unit Chief (1 copy)

Chrysler Corporation, Missile Division, Post Office Box 2628, Detroit 31, Michigan - Attn: Technical Information Center (1 copy)

General Dynamics/Astronautics, Post Office Box 1128, San Diego 12, California - Attn: Library and Information Services (128-00) (1 copy)

Cornell Aeronautical Laboratory, 4455 Genesee Street, Buffalo, New York - Attn: Library (1 copy)

Defense Research Corporation, 4050 State Street, Santa Barbara, California - Attn: Technical Information Office (1 copy)

Douglas Aircraft Company, 3000 Ocean Park Boulevard, Santa Monica, California - Attn: Library (1 copy)

Electro-Optical Systems, Inc., 125 North Vinedo Avenue, Pasadena, California - Attn: Mr. M. Richard Dension, Head,
Aerospace Physics Dept.
Fluid Physics Division (1 copy)

Avco Corporation, Research and Advanced Development Division, 201 Lowell Street, Wilmington, Massachusetts - Attn: D. Walker (1 copy)
R. Detra (1 copy)
J. Luceri (1 copy)

Commander (Code 753) U.S. Naval Ordnance Test Station, China Lake, California - Attn: Technical Library (1 copy)

Space Technology Laboratories, Inc., One Space Park, Redondo Beach, California - Attn: L. Hromas (1 copy)

AUTIC, The Martin Company, Post Office Box 179, Denver, Colorado (1 copy)

McDonnell Aircraft Corporation, Lambert-Saint Louis Municipal Airport, Box 516, St. Louis 66, Missouri (1 copy)

Office of Aerospace Research, Tempo-D, Washington 25, D.C. - Attn: RROSE (1 copy)

Chief, AFSC Office, Room C-107, Bldg. 4488, Redstone Arsenal, Alabama (1 copy)

Lockheed Missiles and Space Company, 7701 Woodley Avenue, Van Nuys, California - Attn: Technical Information Center, Dept. 50-14 (1 copy)

U.S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland - Attn: Dr. R.K. Lobb, Aeroballistics Program Chief (1 copy)
Librarian (1 copy)

Sandia Corporation, Sandia Base, Post Office Box 5800, Albuquerque, New Mexico - Attn: R.W. Henderson (1 copy)
Document Control (1 copy)
E.W. Draper (1 copy)

Department of the Navy, Special Projects Office, Washington 25, D.C. - Attn: Mr. M. Schindler (1 copy)

Director U.S. Naval Research Lab., Washington, D.C. - Attn: Code 2027 (1 copy)

Lockheed Missiles and Space Company, Post Office Box 504, Sunnyvale, California - Attn: Mr. Maurice Tucker (1 copy)

Martin Company, SCI-Technical Library, Mail 398, Aerodynamics Laboratory, Baltimore 3, Maryland (1 copy)

Commanding Officer, U.S. Army Research Office (Durham),Box CM Duke Station, Durham, North Carolina (1 copy)

Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio - Attn: Battelle DEFENDER (1 copy)

Office, Chief of Research and Development, Department of the Army, Washington 25, D.C. (1 copy)

U.S. Army Electronic Research and Development Laboratory, Fort Monmouth, New Jersey - Attn: Technical Library (1 copy)

Director, Ames Research Center, National Aeronautics & Space Administration, Moffett Field, California - Attn: Technical (1 copy)

Rome Air Development Center, Griffiss AFB, New York - Attn: RCLS/J. Segal (1 copy)

Office of Naval Research, Department of the Navy, Washington, D.C. - Attn: Dr. Shirleigh Silverman, Science Director (1 copy)

The Rand Corporation, 1700 Main Street, Santa Monica, California - Attn: Helen J. Waldron, Librarian (1 copy)

National Aeronautics & Space Administration, Aeronautical Research, 1520 H Street, N.W., Washington 25, D.C.
Attn: Mr. Bertram A. Mulcahy, Director, Technical Information Division (1 copy)

Johns Hopkins University, Applied Physics Laboratory, 8621 Georgia Avenue, Silver Spring, Maryland - Attn: Dr. Gibson, Director (1 copy)

Dr. Antonio Ferri, Dept. of Aeronautics and Astronautics, New York University, School of Engineering and Science, Bronx 53, New York (1 copy)

University of California, Lawrence Radiation Laboratory, Livermore, California - Attn: Document Control - C. G. Craig (1 copy)

Lewis Research Center, National Aeronautics and Space Administration, 21000 Brookpark Road, Cleveland 35, Ohio - Attn: George Mandel, Librarian (1 copy)

DASA Chief, Washington 25, D.C. (1 copy)

Chief, Bureau of Naval Weapons (RT), Department of the Navy, Washington 25, D.C. - Attn: Weapons Systems Analysis Division (1 copy)

Bell Telephone Laboratories, Inc., Whippany, New Jersey - Attn: Technical Reports Center, Room 2A165B (1 copy)

Institute of Defense Analyses, Research and Engineering Support Division, Washington, D.C. - Attn: Library (1 copy)

Langley Research Center, National Aeronautics and Space Administration, Langley Station, Hampton, Virginia - Attn: Jean B. Elliott, Librarian (1 copy)

Massachusetts Institute of Technology, Instrumentation Laboratory, 68 Albany Street, Cambridge 39, Massachusetts - Attn: Library, W1-109 (1 copy)

Cornell University, Nuclear Studies Laboratory, Ithaca, New York - Attn: Prof. Hans Bethe (1 copy)

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California - Attn: H. Denslow, Library Supervisor (1 copy)

Guggenheim Aeronautical Laboratory, California Institute of Technology, 1201 E. California, Pasadena 4, California
Attn: Dr. H.W. Liepmann (1 copy)

University of California, Los Alamos Scientific Laboratory, Post Office Box 1663, Los Alamos, New Mexico - Attn: Document Control (1 copy)

Bureau of Naval Weapons Representative, Lockheed Missiles and Space Company (Special Projects Office), P.O. Box 504, Sunnyvale, California (1 copy)

Commander, U.S. Naval Air Missile Test Center, Point Mugu, California (1 copy)

Philco Corporation, Aeronutronic Division, Ford Road, Newport Beach, California - Attn: Technical Library (1 copy)

Vidya, Inc., 2626 Hanover Street, Stanford Industrial Park, Palo Alto, California - Attn: Patricia L. Horn, Security Officer (1 copy)

Systems Engineering Group, Deputy for Systems Engineering, Directorate of Technical Publications and specifications (SEPRR), Wright-Patterson Air Force Base, Ohio 45433 (1 copy)

Headquarters, Aeronautical Systems Div., U.S.A.F., Wright-Patterson, AFB, Ohio - Attn: W. D. Dodd (ASRSMF) (1 copy)
ASQWR (Lt. Hill) (1 copy)
A.M. Prettyman (1 copy)